Indian Institute of Technology Kanpur

AE451A

Experiments in Aerospace Engineering - III

Experiment No. 7

Aerodynamic forces and moments on a generic aircraft model

Submitted By:

Ankit Lakhiwal (180102)

ankitl@iitk.ac.in

Aerospace Engineering Department, IIT Kanpur

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1. Learning Objective

- Use of 3D section of the 3-D wind tunnel.
- Six-component Balance
- Model attitude control system
- Data acquisition system
- Estimation of aerodynamic forces acting on the model under test. The analysis involves calculation of forces and moments.
- Force data acquisition is done in order to estimate the aerodynamic coefficients for performance evaluation of the model under test.Force data is acquired using six component internal balance and is analyzed. Sign convention for forces and moments play an important role in balance data acquisition during the test and data analysis later. Balance data analysis includes forces and moments calculation in various axes system

2. Inroduction and Theory

Principle of operation

Our aircraftmodelis mounted on the balance accurately. Soit transmitsthe load to the balance during experiment. Balance is attached to the mechanism which provides pitching, yawing and rolling moment to the aircraft model. We are using Six component force balance which is a cylindrical body on which an aerodynamics model can be mounted to measure different forces acting on it by aerodynamic loading. Whetstone bridge card (SCXI-1000) is a constant DC voltage supply is required to activate the bridges. For this a SCXI-1314NI card is used which facilitates DC voltage supply. Data acquisition card (PXI-1033) which is the voltage output of the strain gauges is required to be measured under the loading on the balance. For this a data acquisition card PXI-1033 with maximum of 16 voltage input channels is used. Also Labview software facilitated to provide/acquire the input/output voltage signals to/from the strain gauge bridges using a specially built VI program.Usually, non-dimensionalized raw signal (mV/VEx) has been saved during the test and analyzed later.A linear least square fit for the variation of the normalized outputs with respects to a particulars load components is obtained

Sign conventions

In general, right hand rule or Euler's convention is followed for all the axes system. Direction of positive forces and moments in body and wind axes are shown in the figure.

Axes:

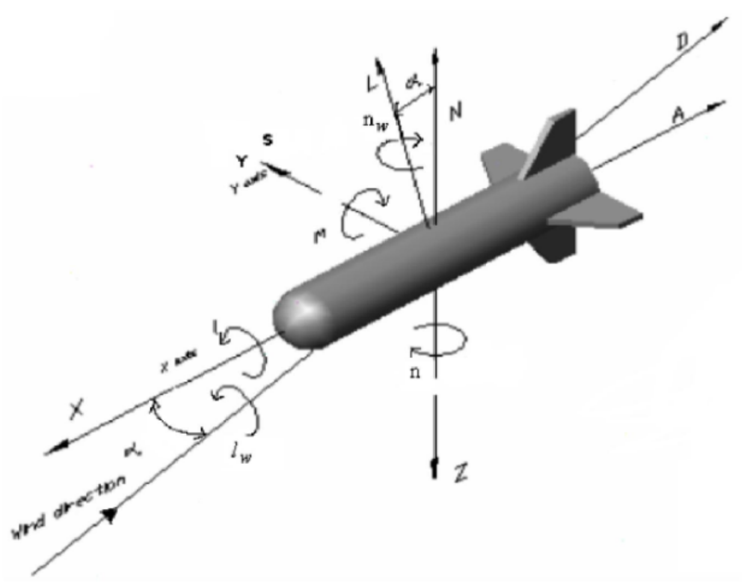
- x- axis : positive forward
- y- axis : positive to starboard
- z- axis : positive downward

Forces in model axes:

- Axial force : A
- Side force : Y
- Noraml force : N

Moments in model axes:

- Rolling moment, l : starboard wing down
- Pitching moment, m : nose up
- Yawing moment, n : nose toward starboard



Forces in wind axes:

- Drag force, D : along the wind direction
- Side force, S : to starboard
- Lift force, L : Normal to wind direction

Moments in wind axes:

- Rolling moments lw : starboard wing down
- Pitching moments mw : nose up
- Yawing moments, nw : nose towards starboard

Force and moments equations

1. Balance axis system

$$\vec{F_i} = C_{ij}\vec{E_j}$$

$$\begin{aligned} \vec{F_i} &= \{A_x, N_1, N_2, S_1, S_2, R_m\} & \vec{E_j} &= \{E_{A_x}, E_{N_1}, E_{N_2}, E_{S_1}, E_{S_2}, E_{R_m}\} \\ A_{x_{bc}} &= A_x & R_{m_{bc}} &= R_m \\ S_{bc} &= S_1 + S_2 & M_{p_{bc}} &= (N_1 - N_2) * d \\ N_{bc} &= N_1 + N_2 & M_{y_{bc}} &= (S_1 - S_2) * d \end{aligned} \tag{1}$$

2. Body axis system

$$\vec{F_B} = T_b^B \vec{F_b} \qquad \vec{M_B} = T_b^B \vec{M_b}$$

$$T_b^B = \begin{bmatrix} cos\alpha_b cos\psi_b & cos\alpha_b sin\psi_b & -sin\alpha_b \\ (sin\phi_b sin\alpha_b sin\psi_b - cos\phi_b sin\psi_b) & (sin\phi_b sin\alpha_b sin\psi_b + cos\phi_b cos\psi_b) & (sin\phi_b cos\alpha_b) \\ (cos\phi_b sin\alpha_b cos\psi_b + sin\phi_b sin\psi_b) & (cos\phi_b sin\alpha_b sin\psi_b - sin\phi_b cos\psi_b) & (cos\phi_b cos\alpha_b) \end{bmatrix} \tag{2}$$

$$where\ \alpha_b = 0,\ \psi_b = 0\ and\ \phi_b = 0$$

$$T_b^B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

3. Wind axis system

$$\vec{F}_w = T_B^w \vec{F}_B \qquad \vec{M}_w = T_B^w \vec{M}_B$$

$$T_B^w = \begin{bmatrix} cos\alpha_w cos\psi_w & cos\alpha_w sin\psi_w & -sin\alpha_w \\ (sin\phi_w sin\alpha_w sin\psi_w - cos\phi_w sin\psi_w) & (sin\phi_w sin\alpha_w sin\psi_w + cos\phi_w cos\psi_w) & (sin\phi_w cos\alpha_w) \\ (cos\phi_w sin\alpha_w cos\psi_w + sin\phi_w sin\psi_w) & (cos\phi_w sin\alpha_w sin\psi_w - sin\phi_w cos\psi_w) & (cos\phi_w cos\alpha_w) \end{bmatrix} \tag{3}$$

$$where\ \alpha_w \neq 0,\ \psi_w = 0\ and\ \phi_w = 0$$

$$T_B^w = \begin{bmatrix} cos\alpha_w & 0 & -sin\alpha_w \\ 0 & 1 & 0 \\ sin\alpha_w & 0 & cos\alpha_w \end{bmatrix}$$

Therefore, the relations of forces at balance, body and wind axes with right hand axes convention are as follow

$$\vec{F}_b = \begin{bmatrix} F_{Xb} \\ F_{Yb} \\ F_{Zb} \end{bmatrix} = \begin{bmatrix} Ax_b \\ Y_b \\ N_b \end{bmatrix}, \vec{F}_B = \begin{bmatrix} F_{XB} \\ F_{YB} \\ F_{ZB} \end{bmatrix} = \begin{bmatrix} -A \\ Y \\ -N \end{bmatrix},\ and\ \vec{F}_w = \begin{bmatrix} F_{X_w} \\ F_{Y_w} \\ F_{Z_w} \end{bmatrix} = \begin{bmatrix} -D \\ S \\ L \end{bmatrix} \tag{4}$$

Subscript 'b' stands for balance axes, 'B' standsfor Body axes and 'w' for wind axes

Moment component are consistent with the positive convention of the axes. Thus equation of moments in the balance, body and wind axes will be

$$\vec{M}_b = \begin{bmatrix} M_{X_b} \\ M_{Y_b} \\ M_{Z_b} \end{bmatrix} = \begin{bmatrix} Mr_b \\ Mp_b \\ My_b \end{bmatrix}, \vec{M}_B = \begin{bmatrix} M_{X_B} \\ M_{Y_B} \\ M_{Z_B} \end{bmatrix} = \begin{bmatrix} l \\ m \\ n \end{bmatrix},\ and\ \vec{M}_w = \begin{bmatrix} M_{X_w} \\ M_{Y_w} \\ M_{Z_w} \end{bmatrix} = \begin{bmatrix} l_w \\ m_w \\ n_w \end{bmatrix} \tag{5}$$

The angles are measured w.r.t. wind axis and clockwise rotation from reference axis to the target axis is considered positive.

3. Equipment's

1. Six component force balance
2. Whetstone bridge card (SCXI-1000)
3. Data acquisition card (PXI-1033)
4. Labview software
5. Aircraft models used to do experiment.

4. Procedure and Measurements

1. Setting the model on six component balance in wind tunnel
2. No wind experiment when no air flow over aircraft model
3. Wind test experimentwhen air flowing over aircraft model in wind tunnel
4. Calculation of aerodynamic coefficients in body as well as in wind axis

Aircraft model parameters

S.No.	Parameters	Dimension
1.	Root chord (c)	0.390 m
2.	Wing span (b)	0.551 m
3.	Planform area	0.1074 m^2
4.	Horizontal displacemt, reference point (dx)	0.21 m
5.	Distance between balance center and force guages (d)	0.035 m

Table 1. Aircraft model parameters

5. Calculation

Force And Moment coefficient Calculation at
Angle of Attack (α) = ~~[illegible]~~ 10.998 deg
At 15 m/s wind speed

① For Balance axis System

$$F_i = C_{ij} E_j$$

C_{ij} = Inverse calibration coefficient matrix

$$\underset{\text{(Volt)}}{E_j} = \begin{array}{cccccc} A_x & N_1 & N_2 & S_1 & S_2 & R_m \\ \end{array}$$

$$E_j = \begin{bmatrix} -0.008721 & 0.017422 & 0.042320 & -0.000206 & 0.000532 & 0.013241 \end{bmatrix}^T$$

$$F_i = \begin{bmatrix} 6.722 & 0.0687 & -0.1931 & -0.0441 & 0.0826 & 0.1438 \\ 0.225 & 14.006 & -0.2987 & 0.3709 & -0.0251 & 0.4992 \\ -0.1334 & 0.1073 & 15.5053 & 0.0024 & 0.7658 & 0.0503 \\ -0.0792 & 0.0643 & 0.0096 & 4.4782 & -0.0737 & -0.2123 \\ 0.0472 & 0.0034 & -0.0975 & 0.0406 & 5.1455 & 0.3240 \\ 0.0231 & 3.1507 & -3.9523 & 0.5971 & 0.6623 & 449.36148 \end{bmatrix} \begin{bmatrix} -0.0087 \\ 0.01742 \\ 0.04232 \\ -0.0002 \\ 0.00053 \\ 0.0132 \end{bmatrix}$$

$$\cancel{F_i = \begin{bmatrix} -6.364 & 2.359 & 6.604 & -1.554 & 2.537 & 5.837 \end{bmatrix}^T}$$
(kg)

$$\cancel{F_i \times 9.8 = [-0.}$$

$$\underset{\text{(kg)}}{F_i} = \begin{bmatrix} -0.0636 & 0.236 & 0.6604 & -0.0015 & 0.00254 & 5.8376 \end{bmatrix}$$

$$\underset{\text{(N)}}{F_i \times 9.81} = \begin{bmatrix} -0.624 & 2.3144 & 6.478 & -0.0152 & 0.0248 & \underset{\text{Nm}}{0.0572} \end{bmatrix}$$

$$Ax_{bc} = -0.624 \text{ N}$$

$$S_{bc} = S_1 + S_2 = -0.0152 + 0.0248 = 0.0096 \text{ N}$$

$$N_{bc} = N_1 + N_2 = 2.3144 + 6.478 = 8.7924 \text{ N}$$

$$\boxed{Rm_{bc} = 0.0572 \text{ Nm}}$$

$$M_{P_{bc}} = (N_1 - N_2) \times d$$
$$= (2.3144 - 6.478) \times (0.35)$$
$$\boxed{M_{P_{bc}} = -1.45726 \text{ Nm}}$$

$$My_{bc} = (S_1 - S_2) \times d$$
$$= (-0.0152 - 0.0248) \times (0.35)$$
$$\boxed{My_{bc} = -0.014}$$

$$\vec{F}_{bc} = \begin{bmatrix} -Ax \\ S_{bc} \\ -N_{bc} \end{bmatrix} = \begin{bmatrix} 0.624 \\ 0.0096 \\ -8.7924 \end{bmatrix} \text{N} \quad \vec{M}_{bc} = \begin{bmatrix} Rm_{bc} \\ MP_{bc} \\ My_{bc} \end{bmatrix} = \begin{bmatrix} 0.0572 \\ -1.45726 \\ -0.014 \end{bmatrix} \text{Nm}$$

— (1)

(2) Body Axis system

$$\vec{F}_B = T_b^B \vec{F}_b \qquad \vec{M}_B = T_b^B \vec{M}_b$$

$$\phi_0 = 0, \quad \psi_0 = 0, \quad \alpha_0 = 0$$

$$T_b^B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

From eq. (1)

$$\vec{F}_B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0.624 \\ 0.0096 \\ -8.7924 \end{bmatrix} = \begin{bmatrix} 0.624 \\ 0.0096 \\ -8.7924 \end{bmatrix} = \begin{bmatrix} -A \\ Y \\ -N \end{bmatrix} \quad \text{--- (2)}$$

$$\vec{M}_B = T_b^B \begin{bmatrix} l \\ m \\ n \end{bmatrix} = \begin{bmatrix} M_{x_b} - (\cancelto{0}{\Delta y F_{z_b}} - \cancelto{0}{\Delta z F_{y_b}}) \\ M_{y_b} - (\cancelto{0}{\Delta z F_{x_b}} - \Delta x F_{z_b}) \\ M_{z_b} - (\Delta x F_{y_b} - \cancelto{0}{\Delta y F_{x_b}}) \end{bmatrix}$$

$$\Delta x = 0.21\,m \qquad \Delta y = 0 \qquad \Delta z = 0$$

$$\vec{M}_B = \begin{bmatrix} 0.0572 \\ -1.45726 - (-0.21 * (-8.7924)) \\ -0.014 - (0.21 * 0.0096) \end{bmatrix}$$

$$\vec{M}_B = \begin{bmatrix} 0.0572 \\ -3.3036 \\ -0.0160 \end{bmatrix} = \begin{bmatrix} l \\ m \\ n \end{bmatrix} \quad \text{--- (3)}$$

(3) Wind Axis System

$$\vec{F}_W = T_B^W \vec{F}_B \qquad \vec{M}_W = T_B^W \vec{M}_B$$

$$\phi_0 = 0 \qquad \psi_0 = 0 \qquad \alpha_W = 10.99^\circ$$

$$T_B^W = \begin{bmatrix} \cos(10.99^\circ) & 0 & -\sin(10.99^\circ) \\ 0 & 1 & 0 \\ \sin(10.99^\circ) & 0 & \cos(10.99^\circ) \end{bmatrix}$$

$$T_B^W = \begin{bmatrix} 0.9816 & 0 & -0.1906 \\ 0 & 1 & 0 \\ 0.1906 & 0 & 0.9816 \end{bmatrix}$$

From eq. (2) & (3)

$$\vec{F}_W = (T_B^W)^T \begin{bmatrix} -0.624 \\ 0.0096 \\ 8.7924 \end{bmatrix} = \begin{bmatrix} -1.069 \\ 0.0096 \\ -8.7504 \end{bmatrix} = \begin{bmatrix} -D \\ S \\ -L \end{bmatrix}$$

$$\vec{M}_W = (T_B^W)^T \begin{bmatrix} 0.0572 \\ -3.3036 \\ -0.0160 \end{bmatrix} = \begin{bmatrix} 0.0555 \\ -1.9924 \\ -0.0143 \end{bmatrix} = \begin{bmatrix} l_W \\ m_W \\ n_W \end{bmatrix}$$

⇒ Coefficients calculation:

$$C_D = \frac{D}{qA} = \frac{1.069}{(136.4263)(1.074)} = 0.0729$$

$$C_S = \frac{S}{qA} = \frac{0.0096}{(136.4263)(1.074)} = 0.0006585$$

$$C_L = \frac{L}{qA} = \frac{8.7504}{(136.4263)(1.074)} = 0.597$$

$$C_{l_w} = \frac{l_w}{qAb} = \frac{0.0555}{(136.4263)(1.074)(0.551)} = 0.0068$$

$$C_{m_w} = \frac{m_w}{qA\bar{c}} = \frac{-1.9924}{(136.4263)(1.074)(0.390)} = -0.3486$$

$$C_{n_w} = \frac{n_w}{qAb} = \frac{-0.0143}{qAb} = -0.001774$$

Force & moment coefficients at 10.99° Angle of attack

$C_D = 0.0729$ $\quad$ $C_{l_w} = 0.0068$
$C_S = 0.00065$ $\quad$ $C_{m_w} = -0.3486$
$C_L = 0.59721$ $\quad$ $C_{n_w} = -0.001774$

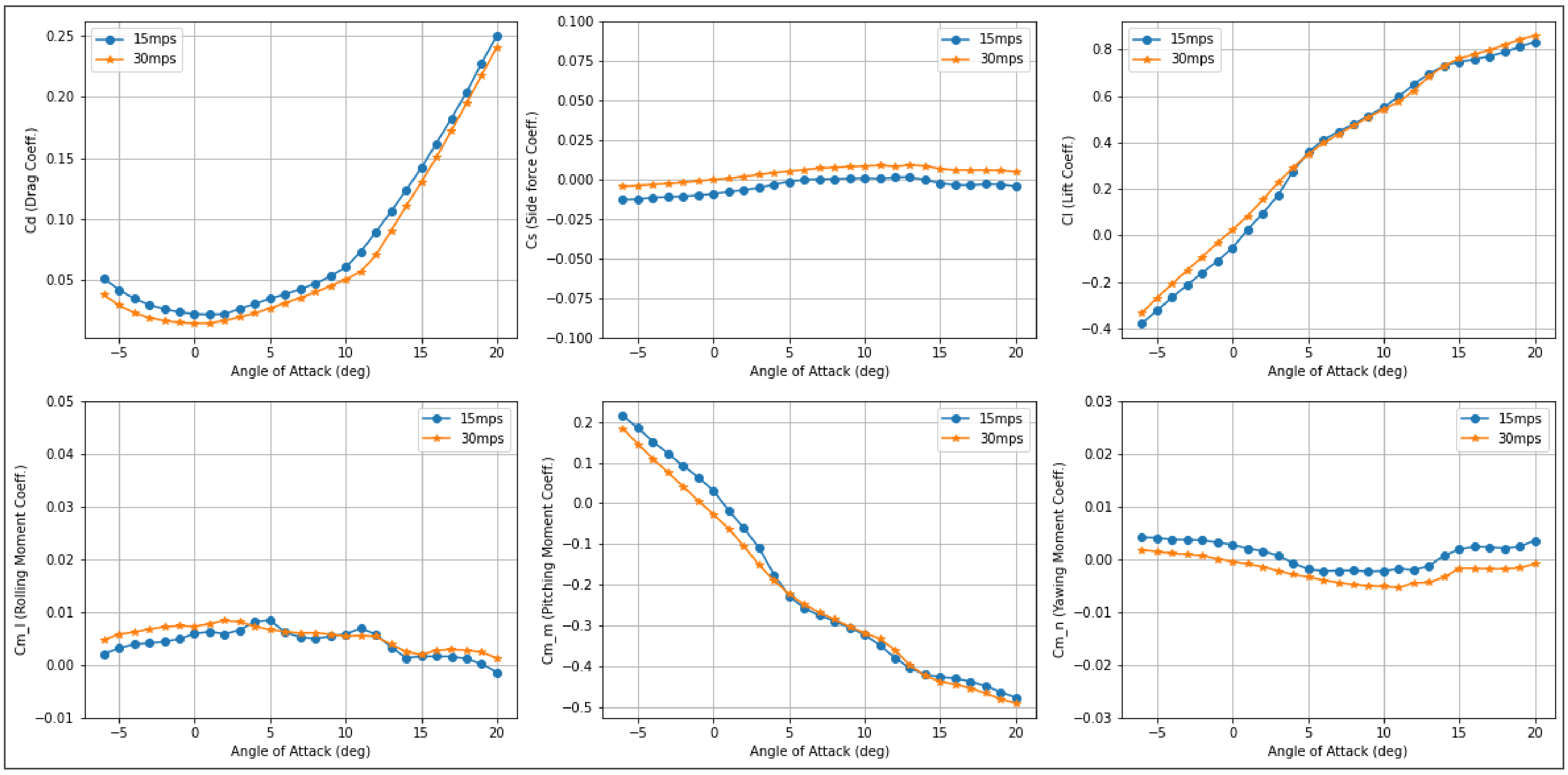
6. Data Analysis

Inverse Calibration Coefficient Matrix

	0	1	2	3	4	5
0	6.722423	0.068790	-0.193090	-0.044077	0.082625	0.143804
1	0.224755	14.005905	-0.298689	0.370984	-0.025113	0.499237
2	-0.133373	0.107297	15.505331	0.002459	0.765804	0.050340
3	-0.079169	0.064270	0.009651	4.475195	-0.073766	-0.212330
4	0.047195	0.003390	-0.097551	0.040600	5.145576	0.324017
5	0.023096	3.150696	-3.952312	0.597108	0.662367	449.361481

Table 2. Inverse calibration coefficient matrix

Wind Axis Coefficient Graph



7. Precautions

1. Check the individual resistance of the bridges.
2. Check the bridge for shorts with the grounds. This should show a very high resistance of the order of mega ohms.
3. DO NOT SHORT THE OUTPUT LEADS ONCE THE POWER SUPPLY IS "ON".
4. Check the direction of the outputs by applying small loads.
5. Allow the bridges to warms up for at least one hour actual measurement.

6. Check the Balance voltage which should not be exceed limit of 6-component strain gage balance

8. Questions

1. What are the different aerodynamic forces acting on a model?

   Ans. Lift, Drag, Side force, Rolling Moment, Pitching Moment and Yawing Moment.

2. What are the working principles of this force balance?

   Ans. The forces are calculated by measuring the strain due to the application of a load which is measured by strain gages (works on Wheatstone bridge principle). Force is calculated from the strain via Hookes Law.

3. What are the other types of balances?

   Ans. Strain gage Load cells, Piezoelectric crystals, Hydraulic load cells, Pneumatic load cells, Magneto-elastic force transducer, etc.,

4. What are the advantages and disadvantages of mechanical balance compared to strain gage type?

   Advantages: The ease with which they can be used, their relatively low cost and the fact that they are reusable. Additionally, some types require no special instrumentation.

   Disadvantages: Relatively bulky size, long gage lengths and the fact that the variety of practical applications is extremely limited.

5. Why we do no wind analysis in force measurement experiment?

   Ans. No wind data is used to calculate the non-aerodynamic (gravity, reaction force, etc) forces acting on the aircraft model, which is later subtracted from the data recorded during the wind experiment to get the aerodynamic forces acting on the model.